BSM PHYSICS AT THE LHC LECTURE I

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THE SM IS SIMPLE AND PREDICTIVE

- $SU(3) \times SU(2) \times U(1)$
- Electroweak sector described in terms of masses and 3 inputs
 - Typically G_{F} , α , M_{Z}
- Particle couplings fixed
 Only unknown parameter
 is Higgs mass
 Testable model !



WHY BSM ?????

- To the best of our knowledge, the SM is a good approximation to most current experimental data
- None-the-less, theoretical and experimental tensions push us to think beyond the SM
- The SM is not entirely satisfactory to theorists

Goal of these lectures is to illustrate the big picture issues and to discuss places where BSM physics might appear

EXPERIMENTAL MOTIVATIONS

- The SM works (so why BSM?)
 - Higgs couplings very close to predictions
- Many negative searches for heavy resonances
 - Off the shelf models need to be tuned to explain non-observation
- Motivation from flavor sector?

THE SM WORKS





CURRENT LIMITS IN THE I-10 TEV RANGE



BSM AND FLAVOR!

• Maybe the new physics is not apparent at high energy scales



HINTS FROM g-2?

• How does this limit BSM physics at the LHC?



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THEORY UNHAPPINESS WITH SM

- Many unanswered questions: dark matter, the pattern of fermion masses (including neutrinos), baryogenesis, strong CP violation, EW hierarchy....
- Why does the SM only have one Higgs doublet?
- What is dark matter?
- What about flavor?
- Why is $\alpha_s >> \alpha$?

A theory of everything would answer these questions





HIGGS HAS SPECIAL JOB IN SM

- Massive W and Z's have longitudinal polarizations (photon does not)
- Longitudinal interactions spoil nice properties of gauge theories:
 - Loops are not finite without Higgs





SM particles have just the right couplings so amplitudes don't grow with energy

UNITARITY HAS REAL WORLD CONSEQUENCES

- The story started in pre-history with the classic paper:
 - Probing the Weak Boson Sector in e⁺e⁻ →W⁺W (Hagiwara, Peccei, Zeppenfeld, Hikasa, 1987)
 - At that time the structure of the 3 gauge boson interactions had not been verified experimentally





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HISTORY: PREDICTING THE SCALE OF NEW PHYSICS

- Fermi theory ($\mu \rightarrow \nu \nu e$) becomes non-perturbative at E ~ 600 GeV
- W boson saves the day
- WW scattering grows with energy and violates unitarity at E \sim 3 TeV
 - Higgs boson < 800 GeV restores unitarity

$$E^{2}/v^{2} \rightarrow O(1)$$

$$MO \ LOSE THEOREMS$$

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This restoration of unitarity requires SM Higgs couplings

 $G_{F}E^{2} \rightarrow G_{F}M_{W}^{2}$

THE NEW PARADIGM

- Past: Guaranteed discoveries ensured by no-lose theorems
 - Beyond the Fermi theory (the W)
 - Beyond the bottom quark (the top)
 - Beyond the electroweak theory (the Higgs)
 - Scattering amplitudes grow with energy without W, top, Higgs....
 - Knew the scale of new physics

Future : No guarantees, need to examine many possibilities

Look for new physics in many places \rightarrow Not just at LHC

NEW PHYSICS

Use precision measurements and effective field theory

Can we determine source of new physics?

No resonance or light resonance or new signatures



Current limits will be strengthened at HL-LHC

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THEORY CLUES

- What kind of insight or motivation is there for looking for specific types of new physics?
- Do we know anything about the scale of new physics?
- Unitarity arguments suggest that precision measurements of couplings useful

SM WORKS AT THE QUANTUM LEVEL

- Use precision measurements to constrain BSM physics (long history starting with LEP and SLD)
- Higgs mass is precision observable



SM predicts relationship between M_t , M_W , and M_H t the loop level

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RESTRICTIONS ON EXTENDED HIGGS MODELS

 ρ parameter (and more generally electroweak corrections) limit extended Higgs sectors (and BSM physics in general)

$$\rho = \frac{\sum_{i} \left[T_{i}(T_{i}+1) - \frac{1}{4}Y_{i}^{2} \right] v_{i}^{2}}{\frac{1}{2} \sum_{i} Y_{i}^{2} v_{i}^{2}} = \frac{M_{W}^{2}}{M_{Z}^{2} c_{W}^{2}}$$

T_i is weak isospin

• $T_i = 1/2$ for doublet; can have as many doublets as you want

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v+h+i\phi_z) \end{pmatrix}, \ T_3 = \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}, \ Q = T_3 + Y \qquad \rho = \frac{\sum_i \left\lfloor \frac{1}{2} \cdot \frac{3}{2} - \frac{1}{4} \right\rfloor v_i^2}{\frac{1}{2} \sum_i v_i^2} = 1$$

• Scalar Singlet doesn't contribute to M_{VV} , M_Z so $\rho=1$ trivially

New scalars typically contribute to other precision EW observables $\ensuremath{\text{S. Dawson}}$

THEORY CLUES: INVISIBLE HIGGS WIDTH?



Interpret Higgs width limit as limit on invisible width, allowing non-SM couplings to vary

SM invisible width is BR $(h \rightarrow vvvv) = 10^{-3}$

Current limit is BR(h to invisible) < 11%

Englert, Kogler, Schulz, Spannowsky, 1708.03332

FLAVOR CLUES?

- Higgs couples proportionally to mass $L = -Y_{ij}\overline{f}_i f_j H \qquad Y_{ij} = \frac{m_{ij}}{v}$
- Suppose there is new physics beyond the SM:

$$\delta L = -\frac{c_{ij}}{\Lambda^2} \overline{Q}_L^i \phi f_R^j(\phi^{\dagger} \phi) + hc \qquad Y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} c_{ij}(\dots$$

- Mass and Yukawas no longer proportional
- Can have flavor changing Higgs decays
 - eg: $H \rightarrow \mu \tau$
- Easy to build models where this is the case

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Smoking gun for new physics!

Diagonalizing the mass matrix

diagonalizes the Yukawa couplings

RARE DECAYS?

- Search for flavor violation in Higgs decays
 - Interesting connection with low energy precision measurements
 - Interesting limits from B physics

Flavor violation occurs in many well motivated models



WHAT ABOUT THE SCALE OF NEW PHYSICS?

- The Higgs operator ($\phi^{\dagger}\phi$) is dimension 2: $V = \mu^2 \phi^{\dagger} \phi + \lambda (\phi^{\dagger} \phi)^2$
- Heavy states contribute quadratically to Higgs mass renormalization
- SM: $\int_{H}^{t} \delta M_{H}^{2} = -\frac{3m_{t}^{2}}{8\pi^{2}v^{2}}\Lambda^{2}$
- Λ is arbitrary cut-off (so just use dimensional regularization....but...)
- Proper interpretation is that Higgs mass is quadratically sensitive to heavy mass scales

EXPANDING THE HIGGS SECTOR

• Heavy mass states contribute to Higgs mass renormalization

 $\mathcal{L} \sim C_V^2(\phi^{\dagger}\phi)V_{\mu}V^{\mu} - C_S^2(\phi^{\dagger}\phi)(S^{\dagger}S) + C_F\overline{L}\tilde{\phi}^{\dagger}l_L + h.c.$



 $\delta M_H^2 = \left\{ \frac{3C_V^2 M_V^2}{16\pi^2} + \frac{C_S^2 m_S^2}{16\pi^2} - \frac{C_F^2 m_L^2}{16\pi^2} \right\}$

- Quadratic sensitivity to high mass scales
- Note that sign of fermion and scalar terms is opposite

* L is SU(2) singlet, I_L is SU(2) doublet



WHY DO WE EXPECT NEW PHYSICS IN LOOPS?



HIGH SCALE DECOUPLING

- Suppose there is a new particle X, with mass $M_X >> M_W$
- SM scattering: $Z \xrightarrow{Z} A_{SM} \sim \frac{g^2}{M_Z^2}$

- Contribution from X: $X = A_X \sim \frac{g_X^2}{M_X^2}$
- Scattering rate: $\sigma \sim \sigma_{SM} + \frac{g^2 g_X^2}{M_Y^2} \rightarrow \sigma_{SM}$

Effects of X vanish as $1/M_X^2$ for weak coupling

Applequist-Carrazone decoupling theorem

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COUNTER EXAMPLES TO DECOUPLING

• Particles whose couplings are proportional to mass don't decouple



• Longitudinal polarizations also change counting (growth with energy):

$$\epsilon_L(p_V) \sim \frac{p_V}{M_V}$$

Enhanced $W_L W_L$ production (relative to $W_T W_T$) in gauge boson pair production

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HEAVY MASS STATES AND SM

 Most familiar example of non-decoupling is gluon fusion with heavy chiral fermion:



• For heavy chiral fermion, $F_{1/2} \rightarrow -4/3$, independent of mass

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• This result can be derived from the effective Lagrangian

 $\phi \to \frac{h+v}{\sqrt{2}}$

$$L_{EFT} = \frac{\alpha_s}{12\pi v^2} \mid \phi \mid^2 G^A_{\mu\nu} G^{A,\mu\nu}$$

WHAT IF THERE WERE A SM 4^{TH} GENERATION?

 Each fermion would contribute the same to gg→ H: t, T, B (in heavy fermion limit)

$$\sigma \to \sigma_{SM} (1+1+1)^2 \to 9\sigma_{SM}$$

SM chiral 4th generation is ruled out by Higgs observation!

This was an early result

*Aside: Vector like quarks allowed



SUMMARY: THEORY CLUES

- New heavy quarks can't be chiral, must be vector-like
- New heavy scalars can cancel quadratic top mass contribution to M_h if they aren't too heavy (MSSM motivation)
- Scalar gauge singlets and doublets don't contribute to ρ ; typically experimental limits can be evaded
- If you mess with SM couplings, you often get unitarity violation--amplitudes growing with energy (motivates precision measurements of couplings)
- SM Higgs coupling are flavor diagonal: $h\!\rightarrow\mu e$ is smoking gun for new physics

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• Higgs decays to invisible very small in SM

BIGGEST SM CLUE

- We haven't found any new particles below the TeV scale
- That's not to say they can't be there, but the models must be carefully constructed to explain this
 - It gets harder and harder to build models.....
- Look for holes in current searches for BSM physics



MANY POSSIBILITIES

- New physics in the Higgs Sector
- New Structures (4-fermion compositeness)
 - New gauge interactions (Z')
 - Supersymmetry
- New signatures
 - Long lived particles

Many other possibilities for new physics at the LHC

 No new particles, use effective field theory and precision measurements at LHC
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MORE HIGGS PARTICLES

MOTIVATIONS FOR MORE HIGGS

- Why should the scalar sector be minimal?
- Extended Higgs sectors can have dark matter candidate
- Extended Higgs sectors can explain baryogenesis with new sources of CP violation in Higgs sector
- Many BSM models require more Higgs

NO SIGN OF MORE HIGGS-LIKE PARTICLES

- No shortage of models predicting more Higgs particles
 - Singlet model, 2HDM, Triplet model, MSSM, NMSSM.....
- Models typically do **not** predict masses of new Higgs particles
- Models typically have a limit where all the new particles are heavy and all the Higgs couplings "look like" the SM
 - Decoupling limit



SINGLET MODEL



PROS:

- Simple (one new scalar, gauge singlet, S)
- Singlet can be portal to hidden sector
- Can give first order EW phase transition for some parameter values
- Can generate enhancements of hh production*

CONS:

No prediction for mass/mixing parameters
 ^{S. Dawson} *Current limits are rate is less than a factor ~6-7 times SM rate

SINGLET MODEL WITH Z_2

• Very predictive: (invariant under $S \rightarrow -S$)

$$V = -\mu^2 \phi^{\dagger} \phi - m^2 S^2 + \lambda (\phi^{\dagger} \phi)^2 + \frac{a_2}{2} (\phi^{\dagger} \phi) S^2 + \frac{b_4}{4} S^4$$

• Physical fields: $h = \cos \theta h_{SM} - \sin \theta S$ $H = \sin \theta h_{SM} + \cos \theta S$

• Physical parameters:

$$M_h, M_H, v, tan\beta = \frac{v}{\langle S \rangle}, \theta$$

• Unitarity bound from $hh \rightarrow hh$

$$an^2eta < rac{16\pi v^2}{3M_H^2}$$
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M_H is heavier Higgs

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Z₂ SYMMETRIC SINGLET MODEL

• Very simple model:



Coupling to light Higgs $\sim \cos \theta$ Coupling to heavy Higgs $\sim \sin \theta$

• If kinematically allowed, $H \rightarrow hh$

 $\Gamma(h) = \cos^2 \theta \Gamma_{SM}$ $\Gamma(H) = \sin^2 \theta \Gamma_{SM} + \Gamma(H \to hh)$

SINGLET MODEL

- Experimental limits on coupling suppression of SM-like Higgs to SM fermions (sin² θ < .12)
- Information from recasting heavy Higgs searches can also be used



Englert et al, arXiv:1403.7191

 $\sigma_{h} = \cos^{2} \theta \sigma_{SM}, \quad \Gamma_{h} = \cos^{2} \theta \Gamma_{SM}, \quad BR(h \to SM) = BR_{SM}, \quad \mu_{h} = \cos^{2} \theta$ $\sigma_{H} = \sin^{2} \theta \sigma_{SM}, \quad \Gamma_{H} = \sin^{2} \theta \Gamma_{SM} + \Gamma_{H} BR(H \to hh), \quad \mu_{H} = \sin^{2} \theta \left[1 - BR(H \to hh)\right]$ * Outdated, but informative40

BRANCHING RATIO $H \rightarrow hh$ can be significant





H can be quite wide; decays predominantly to WW and ZZ

COMPLEMENTARITY OF APPROACHES

- Find heavier Higgs and measure deviations in couplings
- LHC: $\sin^2 \theta < .12$ from h couplings



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RESONANT PRODUCTION OF hh

- Large resonant effects when $M_{H} \sim 2M_{h}$
- NWA approximation accurate for $M_H < 400 \text{ GeV}$



[Dawson, Lewis, arXiv: 1508.05397]



HIGGS SINGLET MODEL WITHOUT Z₂

$$V(\phi, S) = V_{SM}(\phi) + V_{\phi S}(\phi, S) + V_{S}(S)$$
$$V_{\phi S}(\phi, S) = \underbrace{\frac{a_{1}}{2}(\phi^{\dagger}\phi)S}_{V_{S}(S) = b_{1}S} + \frac{b_{2}}{2}S^{2} + \underbrace{\frac{b_{3}}{3}S^{3}}_{S} + \frac{b_{4}}{4}S^{4}$$

- Models without Z₂ symmetry motived by desire to explain electroweak baryogenesis
- (They typically prefer negative a_1 , b_3 and lighter H)
- Can set tan β =0 in this case

More parameters, but still can be studied in terms of mass of H, coupling of h, H to SM fermions, coupling of Hhh

[Profumo, Ramsey-Musolf, Wainwright, Winslow, arXiv:1407.5342; Curtin, Meade, Yu, 1409.0005] S. Dawson

COUNT PARAMETERS

- Original Lagrangian: 8 parameters
- 5 physical conditions:
 - Require (v,x)=(v_{ew},0) is an extremum
 - Two masses: m_h < M_H
 - One mixing angle between the two scalars: θ
- Little freedom remains
 - Free parameters: b₃, b₄
 - Relationship between b₂ and a₂
 - Free parameters: $m_h = 125 \text{ GeV}, M_H, \theta, v_{ew} = 246 \text{ GeV}, x=0, a_2, b_3, b_4$

MOTIVATION FOR SINGLET MODEL

 Non-Z₂ symmetric model can have parameters arranged so as to have strong first order electroweak phase transition



- White dots: consistent with vacuum stability and EWSB minimum
- Blue and purple dots: Consistent with strong first order EW phase transition

Lewis et al, arxiv:1704.05844.pdf

HH CAN GIVE INFORMATION ON ELECTROWEAK PHASE TRANSITION

• Models with scalar singlets can allow first order electroweak phase transition

